ASSESSMENT OF THE TECHNOLOGICAL REQUIREMENTS FOR THE REALIZATION OF PERFORMANCE-BASED FIRE SAFETY DESIGN IN THE UNITED STATES - PHASE I: FUNDAMENTAL REQUIREMENTS

by

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Assessment of the Technological Requirements for the Realization of Performance-Based Fire Safety Design in the United States - Phase I: Fundamental Requirements

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Abstract

Performance-based fire safety design methods are being used or developed in many parts of the world. The bases of several of these methods are the many fire engineering tools and methods developed in the United States. Unfortunately, these tools and methodologies are not being widely applied within the United States. There are many reasons for this, including the lack of performance-based fire and building codes in general use, and, where there are such codes or regulations, the lack of documentation on the availability and application of credible fire safety engineering tools and methodologies for fire safety design. To help assess the technological requirements for realization of performance-based fire safety design in the United States, the Society of Fire Protection Engineers, under a grant from the National Institute of Standards and Technology, Building and Fire Research Laboratory, began a research effort in September 1995. In Phase I of the effort, the intent of a performance-based approach to fire safety analysis and design has been identified, evaluation of performance-based approaches to fire safety analysis and design from around the world has begun, and a framework for a performance-based approach to fire safety analysis and design for use in the United States has been outlined.

Introduction

When signed into law on 26 October 1992, the *Federal Fire Safety Act of 1992* (the Act) became, in essence, the first performance-based fire safety code in the United States. This happened by virtue of allowing *either* the installation of automatic sprinklers *or* the installation of alternative fire protection measures that could be shown to provide *an equivalent level of safety* to that which the sprinklers would be expected to provide.

The wording that allows for *an equivalent level of safety* to automatic sprinkler protection is what makes the Act a performance-based document. Instead of prescribing a list of fire safety measures that must be installed, it defines a level of performance that must be met by the recommended fire safety measures. It is one of the most important, yet most difficult parts of the law for many people to deal with. It is important because it recognizes that although sprinklers can provide a significant level of fire and life safety when properly designed and installed, there are other fire safety measures, that when properly designed and installed, can provide an equivalent level of safety for building occupants without the need for sprinklers. This provides a clear opportunity for undertaking a cost-benefit approach that can result in achieving a desired level of safety performance while realizing an economic benefit as well.

Unfortunately, the use of performance concepts such as *an equivalent level of safety* is new for many engineers practicing in the field of fire safety. As a result, the flexibility and benefits provided in performance oriented codes are not being realized to their full potential. A primary reason for this is the way in which the majority of the members of the fire protection community currently do business: fire safety measures are designed and approved based upon a set of prescribed requirements and are often not engineered based on the specific fire safety needs and objectives of the client. As a result, when faced with a client objective, e.g., "provide a level of safety equivalent to a sprinklered building," many engineers have difficulty translating this into engineering terms upon which to base a design.

This is not to say that equivalency options do not exist and engineering of building fire safety is not performed. However, many of the approaches for determining equivalencies currently used in the United States provide a limited set of options based on prescribed equivalency parameters and do not require the solution to be "engineered." In addition, the solutions are often founded more on expert opinion than on scientific principles, engineering analysis or research data. Although such approaches make the design and approval process for equivalencies very straightforward, they can also impose more limits on a design than necessary, and may not completely consider the performance of the building in a fire situation.

A greater level of flexibility in safe and cost effective design can be attained by applying a performance-based approach to fire safety design. A performance-based design approach is one that begins with a set of well defined objectives, which are translated into specific building fire safety performance objectives that can be stated in engineering terms, and are used as the basis of the fire safety design employing analytical fire engineering calculation methods. This approach is ideal for design consistent with the *Federal Fire Safety Act* and the performance-based codes and standards being developed by the International Code Council (ICC) and the National Fire Protection Association (NFPA), which provide specific performance objectives, such as prevention of flashover and limitation of the fire and its effects to the room of origin. Unfortunately, although there are such performance-based design approaches under development or in use in many parts of the world, there are very few currently available or in use in the United States.

One of the first steps required for realization of performance-based fire safety design in the United States, then, is to outline a framework for performance-based fire safety design that will be widely accepted and used within the United States. This requires identifying what is meant by performance-based fire safety design, evaluating performance-based fire safety design methods from other countries, and outlining a framework for a performance-based fire safety design approach for the United States.

Technology Assessment - Phase I: Assessment of Performance-Based Design Methods

The first phase of this effort required identifying what is meant by performance-based fire safety design and identifying the components of a framework for undertaking performance-based fire safety analyses and designs. This was accomplished by identifying, in general, what performance-based design means, developing a definition for performance-based fire safety design, researching developments in the area of performance-based fire safety design, and outlining a framework for a performance-based approach to fire safety analysis and design.

What is Performance-Based Design?

Performance-based design is a process of engineering a solution to meet specific levels of performance, often stated in terms of performance levels (or objectives) and performance criteria. In structural engineering, for example, the performance levels are often defined in terms of specific limiting damage states against which a structure's performance can be objectively measured.[1] This concept has guided structural engineers for years, especially with regard to design for dead, live, and wind loads. In recent years, the concept has expanded into the realm of design against unacceptable loss due to earthquake loadings as well. In fact, the Structural Engineers Association of California (SEAOC) Vision 2000 project, initiated to provide engineers with a framework for performance-based engineering of buildings against earthquake loads, has defined performance-based engineering as "selection of design criteria, appropriate structural systems, layout, proportioning, and detailing for a structure and its nonstructural components and contents and the assurance of construction quality control such that at specified levels of ground motion and with defined levels of reliability, the structure will not be damaged beyond certain limit states."[1] In short, performance-based design means designing to a specified and measurable level of performance.

What is Performance-Based Fire Safety Design?

Following the concept introduced above, performance-based fire safety design is a process of engineering a fire safety solution to meet a specific level of performance. In recent years, this concept has emerged, in some jurisdictions, as an acceptable means of undertaking fire safety analysis and design in the United States. However, a relatively small percentage of engineers working in the building and fire communities have experience in the application of performance-based approaches to fire safety design. In addition, there are discrepancies in the terminology and definitions used by design professionals, codes- and standards-making organizations, and Authorities Having Jurisdiction that cause unnecessary complications for those applying and reviewing performance oriented approaches to fire safety problems.

To address these fundamental concerns, the first task of this effort was to determine what is meant by "a performance-based approach" to fire safety design and how it relates to the fire protection community in the United States. This was accomplished by identifying and initiating the review of performance-based fire safety analysis and design approaches under development or in use around the world, by convening a focus group to discuss concepts of performance-based codes and performance-based fire safety analysis and design as they pertain to the United States, and proposing, in peer-reviewed publications, a framework for undertaking performance-based fire safety analysis and design. The results of these efforts are described below.

Existing Performance-Based Fire Safety Analysis and Design Methods

The first step towards identifying what is meant by performance-based fire safety analysis and design was to research the topic. As a starting point, the definition of performance-based fire safety engineering used in the SFPE short course "An Introduction to Performance-Based Design for Fire Protection Engineers" was adopted:[2]

An engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and fire effluents; and (4) quantitative assessment of the effectiveness of design alternatives against loss objectives and performance objectives.

With the above definition as a starting point, research was conducted into the evolution of performance-based codes and performance-based fire safety analysis and design approaches. This research effort resulted in the identification of more than a dozen performance-based fire safety analysis and design approaches under development or in use around the world, including:

- *FiRECAM* (NRC, Canada) - computer model[3]
- *FRAMEworks* (NFPRF, USA) - computer model[4]
- *Building Fire Safety Evaluation Method* (Fitzgerald, WPI, USA) - framework document[5]
- *Fire Engineering Guidelines* (FCRC and VUT, Australia) - framework document[6]
- *The Application of Fire Performance Concepts to Design Objectives* (ISO, International)[7]
- Draft for Development on the *Application of Fire Safety Engineering Principles to Building Fire Safety Design* (BSI, UK) - framework document[8]
- *Performance Requirements for Fire Safety* and *Technical Guide for Verification by Calculation*, (Nordic Committee on Building Regulations, NKB, Fire Safety Committee) - framework document[9]
- *Fire-Induced Vulnerability Evaluation (FIVE) Methodology* (EPRI, USA) - computer model and framework document[10]
- *Fire Engineering Design Guide* (University of Canterbury, New Zealand) - framework document[11]
- *Total Fire Safety Design System for Buildings* (MOC, Japan) - equivalent method for compliance with the Building Standards Law[12]
- *Fire Safety Evaluation System* (NFPA, USA) - equivalent method for compliance with the *Life Safety Code®*[13]

A brief discussion of these approaches has been compiled and published in the SFPE monograph, "The Evolution of Performance-Based Codes and Fire Safety Design Methods" (the monograph also includes a brief history and discussion of performance-based regulatory documents).[14]

Despite the presence of this extensive list of analysis and design approaches from around the world, there is not yet a single, generally accepted framework within the fire and building communities for undertaking a performance-based approach to building fire safety analysis and design (although the ISO effort will likely result in a widely available methodology). This lack of a widely-available and generally accepted methodology is due to a number of factors, including the complexity or simplicity of the available methodologies, the lack of data (probabilistic and deterministic), the lack of credible fire safety analysis and design tools, and in some cases, the relationship of a methodology to a specific regulation (e.g., the limitation in use of *NFPA 101A, Fire Safety Evaluation System,* as an equivalent method for compliance with the *NFPA 101, Life Safety Code®*).

However, a review of the above approaches indicates that, at a minimum, the following fundamental concerns should be considered when undertaking a performance-based approach to fire safety analysis and design:

- There is a need to consider the level of acceptable risk (personal and societal).
- There is a need for clear specification of, and agreement to, fire safety goals and objectives, and performance and design criteria.
- There is a need to understand how fire initiates, develops and spreads.
- There is a need to understand how various fire safety measures (active and passive) can mitigate potential fire losses.
- There is a need to understand how people react in a fire situation.
- There is a need to apply credible tools and methodologies in the determination of the above factors.
- There is a need to consider the financial impact of fire safety decisions.
- There is a need to address uncertainties in the analysis and design process.

Given the presence of these common goals from around the world, it was concluded that it should be possible to develop a framework for performance-based fire safety analysis and design that is universally useable and acceptable.

To evaluate the above conclusion, specifically with regard to application of performance-based fire safety engineering (analysis and design) approaches in the United States, the following steps were taken:

- The SFPE convened a focus group of representatives from the building and fire communities to discuss concepts, terminology and definitions for a regulatory system for the United States that includes the use of performance-based design approaches.[15]
- The concept of performance-based fire safety analysis and design, as taught in the SFPE short course,[2] was submitted to and published in a peer-reviewed journal.[16]
- An SFPE Engineering Task Group was established to undertake a more in depth review of various performance-based fire safety analysis and design approaches from around the world and to develop an engineering guide on performance-based fire safety analysis and design.

Focus Group on Concepts of a Performance-Based System for the United States

To help the SFPE gain insight as to how the building and fire communities in the United States viewed the potential structure of a performance-based regulatory system, and to help the SFPE place the engineering aspects of such a system into perspective, the SFPE convened the *SFPE Focus Group on Concepts of a Performance-Based System for the United States* (hereafter referred to as "the focus group" or "the group") in March 1996.

The intent of the focus group was to obtain input from a wide cross-section of the United States' building and fire communities on the movement towards greater use of performance-based codes, standards and fire safety engineering and design methods in the United States. To initiate discussion, participants in the group were given background materials, a working concept for a performance-based system (a three-component system including a code, engineering standards and practices, and evaluation tools and methods), and suggested definitions as bases. They were then asked to comment on the materials provided and to attend meetings to discuss the materials.

The primary objectives for 1996 were to discuss and gain consensus on five key issues:

1. Why does there appear to be such a strong movement towards performance-based codes in the United States?
2. Do we need a performance-based regulatory system for the United States, and what might it entail?
3. What might the components of such a system be?
4. How might the components be developed, formatted, implemented and enforced?
5. What needs to be accomplished before widespread implementation and acceptance of such a system can occur?

To discuss these issues, the SFPE Focus Group on Concepts of a Performance-Based System for the United States convened two meetings during 1996: 25-26 April at the Doubletree Hotel in Arlington, VA, and 23 September at the Sheraton Ottawa Hotel in Ottawa, Ontario, Canada. Over the course of the two meetings, consensus was reached on a number of items related to the above issues. The consensus reached was:

- The United States needs to pursue a performance-based building regulatory system.
- A performance-based system for the United States will likely spawn from the present system, will include explicit policy level goals, functional objectives and performance requirements in the codes (to describe the level of safety that is desired), and will utilize both prescriptive solutions (as we currently have) and performance-based solutions as acceptable means to provide the desired level of safety.
- An initial step in the transition to a performance-based system will be to extract goals and objectives from the current codes (to be primarily accomplished by the codes- and standards-making organizations) and to quantify them.
- Policy level goals must be developed by all interested parties.
- Tools and techniques to measure performance must be developed (the responsibility of many professionals, including the SFPE).
- An engineering guide for developing performance-based solutions needs to be developed (a task the SFPE has initiated).
- A common vocabulary and acceptable definitions need to be developed.
- The overall level of education needs to be raised for everyone in the building and fire communities, especially on performance-based code and design method issues.
- A short-term education goal is to determine what the current code requirements are (in terms of intent and objectives) and to explain why they are required.
- Another short-term education goal is to provide information on the basics and the conceptual background related to performance-based codes and fire safety design methods.
- A long-term educational goal is to provide applications-oriented education to all practitioners.
- Building and fire professionals, especially engineers, need a higher level of qualifications, a higher standard of ethics, and more accountability for a performance-based system to work.
- Good design documentation is mandatory for a performance-based system to work.

- The SFPE should be the facilitator in: a) defining the core competency requirements for those engaged in performance-based fire protection engineering and for those working with performance-based regulations, and, b) building relationships among allied professionals to validate competency (e.g., other engineering disciplines, building officials, architects, etc.).
- The SFPE needs to transmit the information to practitioners that their involvement is critical to the successful implementation of a performance-based system: they will make the difference.
- The SFPE needs to archive knowledge for a performance-based system, such as has been begun with the *SFPE Handbook of Fire Protection Engineering.*
- More outreach is needed to allied professionals to deliver the message of a systems approach to building (fire safety) design.
- Resources are needed for the SFPE and others to deliver on the above items.

This consensus has given the United States' building and fire communities a solid platform from which to build a performance-based building regulatory system. To date, the focus group consensus has played a role in the ICC Performance Committee's effort to develop a performance-based building code, in the development of educational publications and presentations on performance-based concepts, and in outlining technological requirements for the realization of performance-based fire safety engineering in the United States. A key technological requirement is the development of a guideline, or a framework, for undertaking performance-based fire safety designs. (A detailed report of the 1996 activities of the focus group is available from the SFPE.[15])

Framework for a Performance-Based Fire Safety Design Guide for the United States

With input from the United States' building and fire communities on the need for a design guide to support performance-based fire safety design, and with the review of fire engineering design guides from around the world, work has begun on a design guide for the United States. The starting point for development of the guide is the definition of performance-based fire safety design stated previously: an engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and fire effluents; and (4) quantitative assessment of the effectiveness of design alternatives against loss objectives and performance objectives.*

When one takes this definition and views performance-based fire safety design as an engineering process, one finds that the process can be divided into seven fundamental steps:[16]

1. Identification of site or project information,
2. Identification of fire safety goals and objectives,
3. Development of performance criteria & design criteria,
4. Development of fire scenarios,

* An alternate definition that resulted from the focus group discussion defines performance-based fire safety design as an engineering approach to fire safety design based on: (1) agreed upon fire safety goals and objectives, (2) deterministic and probabilistic evaluation of fire scenarios, and (3) a quantitative assessment of design alternatives against the fire safety goals and objectives. Although different wording is used, the two definitions are essentially the same.

5. Development of design fires,
6. Development and evaluation of candidate (trial) designs, and
7. Development of final documentation.

These seven steps, which are found in one form or another in most fire safety engineering guidelines in use or under development,[14] encompass the fundamental aspects deemed necessary for a performance-based fire safety analysis and design approach. As such, they can serve as a solid foundation for development of a framework for performance-based fire safety analysis and design for the United States.

Step 1: Identify Site or Project Information

The first step in the process is to gather information about the site, structure, facility or process. This includes building characteristics, such as size, layout, use, and construction, with particular attention paid to special features such as high-ceiling and large volume spaces (e.g., atria or warehouses), or where high occupant loading might be expected (e.g., malls, auditoriums and stadiums). Operational characteristics relate to specific functions of the building or process, or to needs of the business itself. This category includes such items as the presence of special or unique processes, hazardous material use or storage, areas of high value equipment, and areas where down-time needs to be effectively zero, such as in a semiconductor clean room. Finally, it is important to characterize the occupants. This characterization will vary by use of the building (e.g., residential versus business), and should include such factors as ages, abilities, whether people sleep in the building, and whether people can be considered as individuals that can make their own decisions, or should be classified as groups that need to be led (e.g., families with small children or school children).

Step 2: Identify Fire Safety Goals and Objectives

In general, *goals* are non-controversial statements that are easy to agree with and are measured qualitatively, if measured at all. In the area of fire safety, there are four general goals that fit this definition: protection of life, protection of property, protection of mission, and protection of the environment from the unwanted affects of fire and fire control. In the fire safety design area, one normally sees a fire safety goal expressed as a broad statement that reflects the client's expectation of the level of fire safety desired. This same definition is valid from a code perspective, where the term client may be replaced with the term "public," or from a corporate perspective, using the term "stakeholder."

As an example of how a fire safety goal might appear in a code, consider the following example from the 1994 NFPA Life Safety Code®, "Protect the occupants not intimate with the initial fire development from loss of life."[17] Similarly, a business owner's goal related to protection of mission might be to "protect my business from operational losses due to the damaging effects of fire." These are statements that everyone agrees with. However, everyone may not agree how best to meet them. This is where objectives play a critical role.

Objectives are used to provide more direction as to how a goal might be met, and are normally stated in quantifiable terms. In a performance-based code, one might see a functional objective that describes how a building or its systems will meet a fire safety goal. An example might be to "give people not intimate with the initial fire development adequate time to reach a safe place without being overcome by the effects of fire." In essence, this says that the building and its systems must function in such a way as to enable people to escape to a safe place in the event of a fire in order to meet the goal of life safety.

In performance-based design, however, one could find an objective expressed as a *client loss objective*; that is, some indication of the level of loss that the client can tolerate. An example of this might be to "protect the piece of equipment in Room X against the effects of fire such that a return to full operation can occur within 24 hours." Here again, in order to meet the goal of mission continuity, the objective is to ensure that the equipment is not out of service for more than 24 hours.

Once the functional objectives or loss objectives are clear, one must have a means of identifying the level at which the building and its systems should perform in order to meet these objectives. This is done through statements called performance requirements. *Performance requirements* are statements of the level of performance that must be met by building materials, assemblies, systems, components, and construction methods in order for the fire safety goals and objectives to be met. Not only should one be able to quantify these parameters, one should be able to measure or calculate them as well.

For example, in a performance-based code, one might see performance requirements such as, "limit the spread of fire to the room of origin, alert the occupants prior to smoke spread beyond the room of origin, and maintain tenable conditions in the paths of egress until the occupants reach a safe place." Each of these requirements relates to how the building and its systems should perform in meeting a specific life safety goal and functional objective, and they each can be measured or calculated.

One can develop performance requirements for mission protection as well, such as, "limit the deposition of corrosive products of combustion to less than those quantities that would cause irreversible or unrecoverable damage." In this case, if one knows the limit of product deposition that will cause the damage, and can calculate the species production and deposition rate, one can design to meet this requirement. This leads to the metrics against which the performance requirements will be assessed: the performance criteria and the design criteria.

Step 3: Develop Performance Criteria (Design Objectives) and Design Criteria

In general, *performance criteria* are threshold limits that describe a desired level of performance. For example, a common performance criterion is to prevent flashover in the room of origin. This is something that people can agree on as a "good thing" in preventing the spread of fire; however, it may be insufficient as a criterion for a design engineer who must select a fire protection strategy to accomplish it. Flashover is dependent upon a variety of factors, including compartment geometry and volume; fuel type, loading and characteristics; and compartment ventilation. As such, it is likely that a number of design parameters will be necessary to describe the means of preventing flashover from occurring. These are the *design criteria:* the metrics against which performance criteria are assessed. Design criteria, unlike performance criteria, must be stated in such a manner that they can be directly measured or calculated (e.g., temperature, thermal radiation, and smoke layer depth). These become the criteria on which a design will be based.

To help put all these different requirements and criteria into perspective, consider the following simplified example based on the goal of life safety.

- The *fire safety goal* is to protect those people not intimate with the first materials burning from loss of life. (This is easy to agree with, yet difficult to quantify.)
- To meet this goal, one *functional objective* might be to provide people with adequate time to reach a safe place without being overcome by the effects of fire. (This provides a little more detail: one could infer that protection must be provided against heat, thermal radiation and smoke.)
- To meet this objective, one *performance requirement* is to limit the fire spread to the room of origin. (If the fire does not leave the room, the people outside of the room of origin will not be exposed to thermal radiation or extreme temperature, and their exposure to smoke will be minimized.)
- To meet this performance requirement, one can establish the *performance criterion* of preventing flashover in the room of origin. (This is based on the fact that fire spread beyond the room of origin almost always occurs after flashover when the upper layer gases ignite and spread the fire front.)
- To meet the performance criterion, an engineer might establish a set of *design criteria* such as a maximum upper layer temperature of 500°C and a maximum heat flux at floor level of 20 kW/m^2. (In many cases, several design criteria will be needed.)

Step 4: Develop Fire Scenarios

A fire scenario is a description of a specific fire from ignition, through established burning, to the maximum extent of growth and resulting decay. The range of fire scenarios developed should reflect both probabilistic and deterministic considerations; that is, how likely is it that this fire will occur, and if it does occur, how is it expected to develop and spread. There are many factors that one must consider when developing fire scenarios, including:

Pre-fire situation: building, compartment, conditions.
Ignition sources: temperature, energy, time and area of contact with potential fuels.
Initial fuels: state, surface area to mass ratio, rate of heat release.
Secondary fuels: proximity to initial fuels, amount, distribution.
Extension potential: beyond compartment, structure, area (if outside).
Target locations: note target items or areas associated with client loss objectives along the expected route of spread for fire and fire effluents.
Occupant condition: alert, asleep, self-mobile, disabled, infant, elderly, etc.
Critical factors: ventilation (windows, doors), environmental, operational, etc.
Relevant statistical data.

As one reviews the various fire engineering approaches from around the world, one finds that each one of the approaches considers the above factors, often under the following (or similar) headings:

- Fire initiation and development,
- Smoke development and management,
- Fire spread and management,

- Fire detection and suppression,
- Occupant notification and movement to safety, and
- Fire department notification and response.

Each of these must be considered in any performance-based fire safety analysis and design approach for the United States.

Step 5: Develop Design Fires

A design fire is an engineering description of a specific fire scenario, and may be characterized by parameters such as heat release rate, fire growth rate, species production, species production rate, or other fire related parameters that can be measured or calculated. The most common way of characterizing a design fire is through the use of a fire growth curve. Common characteristics of a fire growth curve include a growth period, peak heat release rate, steady burning period and decay. A curve such as this may be representative of a single item burning in a furniture or room calorimeter, and would need to be adjusted accordingly for use in a design problem, especially where additional items become ignited and contribute to the fire. Design fire curves need to be developed for every fire scenario considered for a compartment, building, structure, or process.

Step 6: Develop and Evaluate Design Alternatives

After the fire scenarios and design fire curves have been developed, the next step is to develop and evaluate design alternatives. A number of fire safety design alternatives should be evaluated at this step, including the code-prescribed requirements. (The code-prescribed requirements often serve as a baseline for evaluation and review, and it is important to know if the code requirements meet the design objectives, exceed them, or fall short of them.) The evaluation process is an iterative one wherein a variety of fire safety measures are evaluated against the design fire curves and the design objectives. Factors such as the addition of smoke detectors or automatic sprinklers, modifications to the ventilation characteristics, and variations to construction materials, interior finish and contents are evaluated here.

Step 7: Documentation and Specifications

The final step in the process is documenting the analysis and design and preparing equipment and installation specifications. The analysis and design report will be a critical factor in gaining the acceptance of a performance-based design. It needs to outline all of the steps taken during the analysis and design, and present the results in a format and manner acceptable to the authorities and to the client (stakeholder).

At a minimum, the report should include:

Intent of the analysis or design: the reasons it was undertaken.
Statement of design approach (philosophy): the approach taken, why it was taken, what assumptions were made, and what engineering tools and methodologies were applied.
Site or project information: hazard analysis and description of the structure, process and/or occupants, e.g., hazards, risks, construction, materials, use, layout, existing systems, occupant characteristics, etc.

Statement of client goals and objectives: the agreed upon goals and objectives of the performance-based analysis or design, who agreed and when.
Performance criteria: the design criteria, the performance criteria and the performance requirements to which they relate, including any safety or reliability factors applied, and support for safety or reliability factors where necessary.
Fire scenarios: the fire scenarios used, bases for selecting and rejecting fire scenarios used, assumptions and restrictions.
Design fire(s): the design fire(s) used, bases for selecting and rejecting design fire(s), assumptions and limitations.
Candidate designs: the design alternative(s) selected, bases for selecting and rejecting design alternative(s) (deterministic, probabilistic), assumptions, limitations and uncertainties. This should include the specific design objective value (Q'_{do}) and the critical fire size value (Q'_{crit}) used, comparison of results with the performance criteria and design objectives and a discussion of the sensitivity of the selected design alternative to changes in the building use, contents, occupants, etc.
Uncertainty factors: any uncertainty (safety, reliability) factors, how they were derived, and/or appropriate references.
Cost-benefit analyses: where cost is a factor in the decision-making process, cost-benefit analyses should be included as well.
Design tools and methods used: the engineering tools and methods used in the analysis or design, including appropriate references (literature, date, software version, etc.), assumptions, limitations, uncertainties, engineering judgments, input data, validation data or procedures, and sensitivity analyses.
Test, inspection and maintenance requirements: test procedures, maintenance schedules, etc.
Fire safety management concerns: discussion on changes in use, contents or materials, training and education for building staff and occupants, etc.
References: software documentation, journal reports, handbook references, technical data sheets, fire test results, etc.

With regard to both the design and the fire safety management aspects, it is important to consider the expected use of the building, throughout its lifetime, when designing the fire safety systems. There should be clear indicators, in the design documentation, as to the limits of the design and to any specific factors that will warrant a re-evaluation or re-design. These may include change of occupancy, significant change of fuel loading, or significant modifications to the building or its systems.

Concerning equipment installation specifications, although one may undertake a performance-based analysis and design, at the end of the day, the installation of the equipment, systems and features will have to be specified in exactly the way it is done today. The analysis and design may consider a variety of features, and the resulting design may have modified sprinkler spacing, exit widths, or number of doors, but the installation specification will still indicate how many, what size, and where they go. In this regard, the future for installers and inspectors will not significantly change. This issue should be addressed as part of any performance-based fire safety analysis and design approach for the United States.

These seven steps are expanded on in the text *Introduction to Performance-Based Fire Safety*.[18]

Uncertainty

There is uncertainty in performance-based fire safety engineering, as in any engineering process, because all is not known about the materials and systems one uses, nor how things may change in the future. (The adjustment of Q'_{crit} (or t_{crit}) to provide a factor of safety, for example, is a means to address uncertainties related to fire and performance-based fire safety engineering.) However, in order to accurately model or predict material or system response, and thus engineer an appropriate solution, it is important to be able to identify and address the uncertainties. Fire safety engineering lags behind other engineering disciplines in this area.

Economic concerns

A performance-based fire safety analysis and design approach would be incomplete if it did not consider some level of cost-benefit analysis. The SFPE Focus Group,[15] as well as others internationally,[14] have identified cost-savings as a critical factor in the transition from a prescriptive-based to a performance-based regulatory system. A principle argument is that money can be saved by minimizing the redundant fire safety measures, prescribed by current codes and standards, when a performance-based design is undertaken. It follows, then that a cost-benefit analysis will be required as part of the design justification. (The review of performance-based approaches from around the world indicates that this issue requires more attention.) This issue should be addressed as part of any performance-based fire safety analysis and design approach for the United States.

Summary

The requirements for, and intent of, a performance-based fire safety analysis and design approach have been defined, and a framework for undertaking such an analysis and design process has been outlined. Indications are that such an engineering approach will be acceptable for use within the United States when all components of a performance-based regulatory system are in place, including the code, engineering standards and practices, and evaluation tools and methods.[15] However, the integration of performance-based fire safety design into the United States' fire and building communities requires much more:

- Technology development will be required to fill any gaps in current technology that are identified during the technology assessment stage and to ensure that the necessary engineering tools and methodologies are available for fire protection professionals.
- The ongoing education of engineers, building and fire authorities is necessary for the transfer of knowledge to those individuals who will develop and approve performance-based designs.
- To ensure that the methods and tools integrated into the regulatory system adequately address the public's perceptions of risk and liability, research in the area of public policy is needed.
- Finally, regulatory infrastructure support is required to introduce the concepts of performance-based design tools and methodologies into building codes and insurance requirements and to ultimately gain the acceptance of these tools and methodologies within the United States' regulatory system.

If future support is available to address these issues, the widespread integration of performance-based fire safety design approaches into the United States can be realized.

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References

[1] Hamburger, R.O., Court, A.B. and Soulages, J.R., "Vision 2000: A Framework for Performance-Based Engineering of Buildings," Proceedings of the 64th Annual Convention, Structural Engineers Association of California, 19-21 October 1995, pp. 127 - 146.

[2] Meacham, B.J., and Custer, R.L.P., SFPE Short Course *Introduction to Performance-Based Design for Fire Protection Engineers*, Society of Fire Protection Engineers, Boston, MA, USA, 1994-1996.

[3] Beck, V.R. and Yung, D., "A Cost-Effective Risk-Assessment Model for Evaluating Fire Safety and Protection in Canadian Apartment Buildings," *Journal of Fire Protection Engineering*, Vol. 2, No. 3, pp.65-74, 1990.

[4] Bukowski, R.W., Clarke, F.B., Hall Jr., J.R. and Stiefel, S.W., National Fire Protection Association, *Fire Risk Assessment Method: Description of Methodology*, National Fire Protection Association Research Foundation, Quincy, MA, USA, 1990.

[5] Fitzgerald, R.W., *Building Fire Safety Evaluation Method*, Worcester Polytechnic Institute, Worcester, MA, 1993.

[6] Fire Code Reform Centre, *Draft Fire Engineering Guidelines*, Sydney, Australia, March, 1996.

[7] ISO/WD 13387, *The Application of Fire Performance Concepts to Design Objectives*, May 1995

[8] Warrington Fire Research Consultants, *Draft British Standard Code of Practice for the Application of Fire Safety Engineering Principals to Fire Safety in Buildings*, Warrington, UK, 1993.

[9] Nordic Committee on Building Regulations, NKB, Fire Safety Committee, *Performance-Requirements for Fire Safety* and *Technical Guide for Verification by Calculation*, NKB, Helsinki, Finland, 1995.

[10] Mowrer, F.W., *Methods of Quantitative Fire Hazard Analysis*, Electric Power Research Institute, Report Number TR-100443 (distributed by SFPE, Boston, MA), 1992.

[11] Buchanan, A., *Fire Engineering Design Guide*, Centre for Advanced Engineering, University of Canterbury, Christchurch, New Zealand, July 1994.

[12] Ministry of Construction, *Kentikubutsu no Sogu Koka Sekkeihov (Total Fire Safety Design System of Buildings)*, the Building Center of Japan, Tokyo, Japan, 1989.

[13] NFPA 101A, *Guide on Alternative Approaches to Life Safety*, National Fire Protection Association, Quincy, MA, USA, 1995.

[14] Meacham, B.J., "The Evolution of Performance-Based Codes and Fire Safety Design Methods," Society of Fire Protection Engineers, Boston, MA, USA, August 1996.

[15] Meacham, B.J., "Report on the 1996 Activities of the SFPE Focus Group on Concepts of a Performance-Based System for the United States," Society of Fire Protection Engineers, Boston, MA, USA, January 1997.

[16] Meacham, B.J. and Custer, R.L.P., "Performance-Based Fire Safety Engineering: An Introduction of Basic Concepts," *Journal of Fire Protection Engineering*, Vol. 7, No. 2, 1995.

[17] NFPA 101, *The Life Safety Code®*, NFPA, Quincy, MA, 1994.

[18] Custer, R.L.P. and Meacham, B.J., *Introduction to Performance-Based Fire Safety*, SFPE and NFPA, Quincy, MA, 1997.